PERFORMANCE BASED DESIGN OF A NEW VIRTUAL LOCOMOTION CONTROL

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ABSTRACT

The ability to simulate walking around in the environment is a key element missing from most of today's joint forces simulations. A number of sensor-based techniques are widely used to maneuver through Virtual Environments but they introduce artifacts into the interaction. Mechanical motion platforms have also been applied to surmount these difficulties, but they tend to exhibit different but equally troublesome side effects of their own. This paper examines the interrelationships between virtual motion control and other critical actions soldiers need to perform in VE. The goal is to allow the user to maneuver through VE in as similar a manner as possible to walking through the real world. If the interactions between different controls and sensory feedback can be made comparable to the interaction between actions in the real world, then there is hope for constructing an effective new technique. Human performance requirements are viewed from an analytical standpoint: pointing out the interactions between a full set of virtual controls that would allow the user to act, sense, and react to their environment. Candidate solutions are discussed as the analysis is developed. This has lead us to a promising new design for sensor-based virtual locomotion called Gaiter, introduced in this paper.

THE TECHNOLOGY AND ITS USE

Virtual locomotion is a control technique for allowing a person to move naturally over long distances in the Virtual Environment (VE), while remaining within a relatively small physical space. Ideally such an interaction technique will allow users to perform the same coordinated actions and move with the same agility in VE as they do in the real world. Virtual locomotion is essential for constructing Individual Combatant Simulators where the soldier interacts directly with the surrounding environment. Previous military simulators have focused on vehicular weapons platforms where motion was controlled through the same kinds of control devices that are used to pilot the actual vehicle. Either actual or reduced cost versions of the controls used to pilot aircraft or drive a tank can be used in flight and tank simulators. This made it relatively straightforward to attain a high level of realistic interaction. For a locomotion simulator, the user's physical body is the control device and the user's avatar (representation of the user's body in VE) is the "vehicle" being controlled. This changes things considerably, calling for new kinds of control actions.

DoD needs individual combatant simulators for both training and analysis. Such simulators can be used to train soldiers in team operations and tactical doctrine. They can be used to familiarize a group with a specific environment, and to plan and rehearse operations in that environment. An accurate VE model of an embassy could be used to train a team to carry out an embassy evacuation. For analysis, it is important to adequately simulate the performance of individual combatants in combined force simulations to make the simulation more complete and enhance its validity. The individual combatant is the "missing element" in today's military simulators. When this element becomes available, combined force simulations can be used to analyze and evaluate new tactics and operational plans. It will also allow new technology (for foot-soldiers, or jeopardized by foot-soldiers) to be studied with a comprehensive simulation.

HUMAN FACTORS ISSUES INVOLVED

A Framework For Analysis

The goal is to find a virtual locomotion control technique as similar to actual locomotion as possible. But exactly how should it be similar? We approach this question through a careful analysis of the interrelationship between natural and control actions.

Specifying A Control Technique

It is useful to divide a control technique into two parts: the *control action* made by the user and the *controlled effect* produced by the computer system. Since in this case the control technique is used to mimic an action performed in the

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real world, there is a corresponding *natural action* and *natural effect*. For virtual locomotion the natural action is perambulation (walking, running, sidestepping, etc.), the natural effect is real motion (physical displacement), and the controlled effect is virtual motion. There are many alternative control actions that can be used for virtual locomotion. They will be considered in terms of the analytical framework developed in this section.

Interaction With Other Natural Actions

Natural locomotion interacts with a wide variety of other actions. These actions include looking (directing both the head and eyes), manipulation (typically involving the hands, as in pointing a rifle), posturing (moving parts of the body, for purposes other than looking, manipulation, or locomotion), and thinking. Thinking is included because it is something the user does which interacts with other actions, including locomotion. Often the expression "cognitive load" is used to describe how thinking can limit or be limited by the performance of other actions.

Components Of Locomotion

Locomotion control will be divided into two components: control over the direction of motion (steering) and the rate of motion (speed). Steering may include a facility for sidestepping (i.e., moving in a direction other than where the torso is oriented).

Simulating A Natural Capability

The goal of simulated locomotion is to provide a control to maneuver through VEs as naturally as possible. We now have the terms to state this requirement a little more formally. (1) The control action should be similar to the natural action with respect to their intrinsic properties (constraints on movements, caloric energy expenditure, etc.). (2) The control action should interact with other actions (looking, manipulation, posturing, and thinking) in a similar manner to the way the natural locomotion interacts with other actions (e.g., freeing the hands for manipulation and allowing a normal level of coordinated head, arm, and leg movements). (3) The components of the control action (steering and speed control) should interact with each other as the components of the natural locomotion interact. (4) The controlled effect should be similar to the natural effect (i.e., the rate and precision of movement should match). This is clearly a tall order for any virtual locomotion control to meet, but it provides a basic set of criteria which can and should be applied to all candidate techniques.

Compatibility With Turning The Body

A great deal of compatibility with other natural actions can be achieved by having the user turn in VE by physically turning the body. This allows actions like turning the head, pointing the hand, or wielding a weapon to be performed as a natural coordinated motion. It also allows the reflexive orientation a person might have towards or away from a stimulus to be used effectively (e.g., turning one's head to view the source of an unexpected sound). Another advantage of using the natural action of turning is to avoid a potential sensory conflict. People sense turning through their visual, aural, haptic, and vestibular systems. They build up a sense of their orientation in an environment through the temporal integration of this information. Peoples' vestibular sense of motion contributes to their ability to navigate through virtual environments.

We therefore prefer to treat turning the body as an action separate from locomotion, limiting locomotion to the control of the translational motion of the body through space. Steering is still required to control the direction of this motion. Although this eliminates the need for the control action to encompass turning, it imposes the constraint of having the control action be compatible with physical turning. The user should be able to perform virtual locomotion while turning, and the path traversed should vary accordingly.

The body can be turned in several different ways. Most of the time, people step to turn: by lifting and planting their feet in a different direction on each successive step, the body turns to face a new direction. People also pivot on their feet to turn. Here the foot is turned while it continues to support a person's weight. There are one- and two-footed pivots. Pivoting provides an means of turning the body that is more economical in terms of both time and space than stepping to turn, particularly critical in martial situations.

Compatibility With Real Motion

It is highly desirable for the virtual locomotion control to be compatible with other sorts of postural movements like bending at the waist or crouching down. These may be thought of as special purpose actions - essential for certain tasks. A user might bend to look around a corner, or crouch to hide behind an embankment. It would be desirable if those motions could be made in a natural manner while performing virtual locomotion. We do not want users to learn an entirely new vocabulary of control actions just to allow them to move in different postures.

It is also desirable to allow virtual locomotion to be intermixed with natural locomotion. The user could move forward in VE by making control actions or by taking actual steps (albeit over a limited range). Physical movements work well in VE, but must remain within tracker range and within the available space.

Candidate Control Actions

A variety of control actions can be performed to steer and set the speed of motion through the VE. This section will describe sensor based controls that have been employed for this purpose. The most obvious and widely used steering technique is that of pointing. With a vehicular control, the user's body remains fixed in the vehicle and a rate dependent pointing device, like a steering wheel, is used to turn the vehicle. In an individual combatant simulator, the user can turn the body, so pointing can be direct.

Steering Controls

Head-based steering is probably the most widely used steering control for VE systems. It is economical because the same position tracker used to determine the user's field-of-view is used to control the direction of motion. Other advantages of head-based steering are that it "encourages" the user to look where s/he is going, and the hands are free for manipulation. The disadvantage is that looking and moving are no longer independent. The user cannot turn the head to look to the side while moving without altering the path. Bowman demonstrated this problem by asking users to walk to a position pointed at by an arrow in VE [Bowman, Koller, & Hodges, 1997]. Users had to keep turning to look at the arrow as they moved toward the desired position; the act of looking interfered with their motion. The task was much easier to perform using hand-based steering.

Hand-based steering techniques determine direction either from where the arm is pointed, where a hand-grip is pointed, or where a finger is pointed when an instrumented data-glove is worn. Hand-based steering frees the head for looking and allows the user to move sideways relative to the head or body. The disadvantage is that the control interferes with manipulation. The hand is occupied so that using the hand for other tasks leads to conflicts and interruptions. The user also must remain aware of the significance of where the hand is pointed.

Torso-based steering frees the head for looking and the hands for manipulation, but it does not support sidestepping. Often people move in the direction where the front of their torso is pointing, but sometimes they do not. A soldier aiming a rifle across his chest may prefer to advance in the direction he is aiming.
There are three approaches to lean-based steering: tilting the upper torso (bowing), shifting weight relative to one's feet, and shifting one's weight relative to a platform. All three kinds of leaning provide hands-free operation and can support sidestepping. Fairchild, Lee, Loo, Ng, and Serra, [1993] implemented a system based on shifting the user's head position by tilting the upper torso (bowing). This control is incompatible with the user tilting the torso for other purposes. The second approach, shifting weight relative to the feet (i.e., to the basis of support) is of limited use because the continuity is broken when a user steps to turn.

The third type of lean-based control is shifting one's weight relative to a platform. Max Wells at the University of Washington's HIT Lab has developed such a system [Wells, Peterson, and Aten, 1996]. Motion is controlled by moving one's body locally, relative to a central neutral position. When immersed wearing a head-mounted display, the user might lose track of where s/he stands with respect to the neutral position. The direction and rate of optical flow provides one indication of where the user is situated. A set of elastic straps attached to a ring around the user's waist gives haptic feedback, pushing the user back towards the neutral position. The directional coordinate frame is relative to a fixed external point in space, an unnatural condition that produces interesting side effects. This makes turning the body and controlling the direction of motion even more independent than they are with natural locomotion. The user may choose to move in one direction and then turn to face in another, making it as easy to "run" backwards as forward. This approach is incompatible with physical locomotion because velocity is controlled by relative position of the body.

Speed Controls

Speed can be controlled using finger pressure, by the degree of leaning (when leaning is used for steering), by the rate at which the user steps in-place, or by the degree of leg movement when the user steps in-place. Only the use of finger pressure will be discussed in this section. Often a pair of binary switches attached to a hand control are used to invoke either forward or backward virtual motion. This is a widely used technique, easy and inexpensive to implement. We have tried using pressure sensitive buttons and recommend their use because it provides a smooth way of varying speed. A major advantage of hand controls is that they work independently of head, torso, and leg movement and are thus compatible with a wide range of physical motions. The primary drawback of using the hand to control speed is that it interferes with using the fingers for manipulative tasks. As VEs become richer and engage the user in more complex tasks, they require a greater commitment of the user's hands for manipulation. This is most evident for combat systems where the user needs to hold and aim a weapon both at rest and in motion. A second drawback of using hand controls with head-mounted displays is that the user cannot directly see how his hand holds the grip or how fingers touch the buttons. This limits the number of buttons the user can deal with.

REVIEW OF THE STATE-OF-THE-ART

This review will cover both mechanical motion platforms and a promising new sensor-based virtual locomotion system.

Mechanical Locomotion Systems

Uni-directional Systems

A number of mechanical solutions have been proposed. One class of device is the uni-directional systems that limit movement to one direction and require a special control action for turning the virtual world around the user. An early system is the treadmill used at University of North Carolina in their Architectural Walkthrough System [Brooks, Airey, Alspaugh, Bell, Brown, Nimscheck, Rheingans, Rohlf, Smith, Turner, Varshney, Wang, Wber, & Yuan, 1992]. It uses a handle in front that the user twists to steer. They report that the treadmill is disorienting, probably because there is no true sense of turning which is helpful for route learning. Spinning the virtual world about the user produces an odd transient effect. Other uni-direction systems possibly suffer from the same disadvantage. Sarcos Research Corporation developed the TREADPORT, a large treadmill that allows the user to stand, kneel, sit, and lay prone [Youngblut, 1996]. The user is tethered for safety. OSIRIS, developed by the US Army's Night Vision Laboratory, is a stair-stepper device that can only be used upright [Lorenzo *et al.*, 1995]. It can present forward motion only; a hand control is used for steering. The Individual Soldier Mobility Simulator (ISMS) was developed by Sarcos Research Corporation in conjunction with the Army Research Institute. The user stands on two robotic arm boot plates that create the sense of walking or running over different terrain, and ascending or descending stairs [Lorenzo *et al.*, 1995].

Multi-directional Systems

Other mechanical systems allow the user to move in multiple directions. Sarcos Research Corporation's Uniport is based on a unicycle [Lorenzo, Poole, Deaso, Lu, Kekesi, Cha, Slayton, Williams, Moulton, Kaste, MacKrell, Paddison, Rieks, Roth, & Wodoslawsky, 1995]. The user remains in a seated position and turns around a pivot point by applying torque to the seat. This engages a motor to turn the seat at a controlled rate. (This system is at the borderline between a vehicular and locomotion control.) The user's hands are free to hold a gun or other objects.
The Virtual Perambulator [Iwata and Fujii, 1996] uses a sliding motion of the feet to indicate walking. The user wears sandals with low friction film on the middle of the sole and a rubber brake pad at the toe. The user glides on a low friction surface by pushing the waist against a hoop that surrounds the user and sliding the feet. A position sensor attached to each ankle and contact sensors on the bottom of each foot allows the system to recognize the length and direction of each step to specify the movement in VE. An earlier version used roller skates instead of the low friction film. The placement of the hoop at waist level does not allow a user to hold an object by the side.

The Omni-Directional Treadmill (ODT) developed by David Carmein of Virtual Space Devices Inc. [Darken, Cockayne, & Carmein 1997] allows the user to walk in any direction. The mechanism consists of a pair of conveyor belts nested one inside the other. Each track moves horizontally and the tracks are oriented perpendicularly to each other. The outer track has rollers on it so that it can transmit the motion produced by the inner track. The rollers can thus convey motion in any direction to the user's feet resting upon it. The active surface of the motion platform measures 50"x 50". A control system is used that seeks to keep the user centered in the middle of the platform. The system is very effective at

allowing a user to walk in a straight line in any direction. People have little difficulty accelerating along a straight path. Turning while accelerating can lead to a misalignment between the user's direction of translation and the centering motion of the mechanism. This is apt to make the user lose his/her balance and stumble. Even turning in-place can be difficult because the tracking system registers the motion and compensates for it by moving the surface under the user's feet. Sometimes the dynamics of natural locomotion go beyond what the ODT can support. People can decelerate very quickly, coming to a full stop in a single step, and if they pivot while walking fast they can redirect their motion even more rapidly. Further, people perceive linear and angular acceleration using their vestibular system. A user immersed in VE, standing on a "perfect" motion platform would have the sensation that the vestibular perception of linear acceleration were "turned off". This alone will make it difficult to perform certain actions, even if the dynamic response of a motion platform were perfect.

First Attempt Using Walking-In-Place

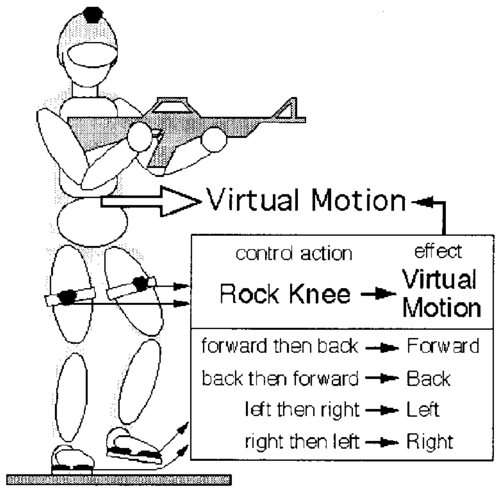
The first virtual locomotion system we implemented and tested used a combination of torso-based steering and step-based speed control. Sidestepping was not supported. A position tracker was attached to the user's waist and pressure sensors were mounted under the ball and heel of each foot on the insoles of their shoes. The basic idea was to initiate virtual motion when the user took an in-place step and use the rate of stepping to control speed. The system also had to be able to distinguish between stepping to turn and stepping in-place to initiate virtual motion. We made the mistake of putting the burden of making this distinction on the user. Forward and backward virtual motion were indicated by pushing off the ball or heel of the foot, respectively. Flat footed steps produced no virtual displacement and were to be used for stepping to turn. The user could also turn while advancing in VE by pushing off the ball of their foot while stepping to turn in-place. This was easy to do when the user concentrated on it, and the computer had no problem recognizing these distinctions. But users tend to get a little "sloppy" when they started thinking about something other than how they stepped. Although ninety percent of their steps indicated their intention, the remainder is enough to spoil the technique. Unintentionally movement, or missing a step is quite disconcerting.

Gaiter: Our New Locomotion Control

We developed a second generation locomotion control to allow the user to more naturally control their movements (without having to concentrate on their footsteps) and to support sidestepping. We call the new system *Gaiter.* Its design is based on generalized classification of human gait that encompasses sidestepping and in-place stepping as well as forward stepping.

The user walks in-place to walk through VE. The user can move in any direction by rocking the knees. Forward virtual motion is achieved by simply walking in place. In this case the knees rock forward then back. To take a virtual sidestep to the right the user lifts his right knee up to the right and then drops it back down (to the left); the left foot should be raised and lowered on alternate steps, but need not rock horizontally. Backward virtual steps are taken by rocking the knees backward first then forward. The user can rock the knees along a diagonal path to move diagonally through VE. The direction and degree of virtual motion is determined by direction and degree with which the knee moves. Virtual displacement is a function of both how far the knees swing and the stepping rate, as physical displacement is a function of both stride length and stepping rate.

Gaiter employs a hybrid sensor system. Position trackers placed on the knees register knee motion. Pressure sensors placed on shoe insoles under the ball and heel of each foot register ground reaction forces. The pressure sensors help determine the timing of each step, punctuating knee motion. Pattern recognition software distinguishes between steps to turn, in-place steps, and actual steps. Since the system can distinguish between them, it can allow the user to intermix virtual and actual steps. Virtual steps move the user in the VE while remaining stationary in the real world.



Gaiter: a new virtual locomotion control being developed at NRL. The user walks in-place to walk through VE. Steps are characterized using a combination of position trackers and pressure sensors

Actual steps move the user the same distance in both the virtual and real world. Actual steps provide the most natural and accurately judged movements but their range is limited, so virtual steps are used to cover large distances.

Features Of Gaiter

Many of the "realistic" features of Gaiter derive from its adoption of leg motion as the control action. It operates in the appropriate coordinate frame of reference: the direction of knee movement with respect to the surrounding environment. Virtual motion may be made in any direction. Sidestepping is an inherent part of the technique. It is compatible with turning the head and body, using the hands for other tasks, a variety of postural movements, and actual walking. The system can be tuned to preserve metrics between physical and virtual space. Knee movement can be scaled and mapped into virtual displacement. The system is responsive; the pattern recognition system does not have to wait for the gesture to be complete before responding to knee movements. Virtual motion occurs as the knees rock. The equipment used to implement Gaiter is compact and relatively inexpensive. A wireless version can be built today, albeit at greater expense than using tethered sensors.

The basic limitation of Gaiter is that walking and running in-place are not the same as actual walking and running. They use somewhat different muscle sets in somewhat different ways. The user does not physically accelerate along the path of motion or build up momentum by running faster in place. (It may be possible to simulate the latter effect by increasing virtual velocity as successive strides are made, but this may make the requisite deceleration seem more artificial.) It will be possible to tune the system to match particular attributes of natural locomotion (e.g., perceived velocity, natural cadence, caloric expenditure, etc.) but it is unlikely that one set of tuning parameters will satisfy all criteria.

Experimental Evaluation

We are currently running pilot studies comparing three different sensor-based virtual locomotion controls: head-based, hand-based, and leg-based (Gaiter). We have started by using the set of locomotion tasks described as part of VEPAB (ARI's VE Performance Assessment Battery [Lampton, Knerr, Goldberg, Bliss, Moshell, & Blau, 1994]). We also have models of the Quantico Village database developed by Paradigm, Inc. for the Team Tactical Engagement System for NAWC/TSD and the Ex-USS Shadwell ship interior developed Dave Tate at NRL [Tate, Sibert, & King, 1997]. This gives us a variety of interesting virtual spaces to walk through. We are tuning the current version of Gaiter to make it match peoples' natural strides. The tasks we will use in the comparative experiment range from simple locomotion down hallways and through rooms, to the more complex task of clearing a building by pointing and clicking at targets while minimizing one's exposure to them. Our hypothesis is that people will perform tasks differently using the three different controls and the sequence of actions (including looking, moving, and manipulation) they perform using the leg-based control will best match the sequence of actions used to perform the task in the real world.

LIMITATIONS OF THE TECHNOLOGY

There are many limitations to the sensors, processing systems, and displays used to construct today's VE systems. Spatial position trackers have a limited range, are sensitive to metal and interference from other sources, and are often tethered. Currently available head mounted displays light weight enough to wear while walking offer a limited field-of-view (typically 50-degrees), a limited display resolution (typically 640 x 480 pixels), a fixed depth of focus, and are often tethered. Current rendering systems provide limited realism of real-time imagery. The lag due to sensor transmission, image generation, and display contributes to motion sickness [DiZio & Lackner, 1992].

There are clearly limitations to the physical interaction provided by VE systems. In terms of locomotion the ground surface is almost always flat, with fixed surface characteristics. This could be improved by employing a hydraulically tilted floor, with adjustable surface compliance. The remaining omission would then be the absence of the collision forces made contacting walls and other raised surfaces. The challenge will be to add these features while keeping the system safe enough to use without falling.

Consequences Of Unrealistic Interaction

What happens when the requirements for interactive realism stated earlier do not hold; when similarity of (1) action, (2) interaction, (3) component actions, or (4) effect are not fully attained? The actions must be the same for the user to develop the right set of coordinated reflexes. The capability (effect) must be the same for users to learn when to apply it, to incorporate it into strategies, and to avoid changing their strategy to *compensate* for its absence. Compensation is bad because it means that users are adopting different practices and approaches in VE than they would use in the real world.

In terms of isolated capabilities, capabilities can be lost in VE, new capabilities can be gained, and the control action can alter the way a capability is used. All of these cases are departures from realistic task performance. If a control lets the user effortlessly move at a rapid speed, the user might carry out rehearsal missions in VE that would be impossible to accomplish in the real world. In terms of interacting capabilities - the control action can preclude other capabilities (e.g., not being able to stop quickly may discourage rapid motion), the control action can free the user to perform extra actions (e.g., a technique that supports backwards motion while the user stands at rest would allow the user to aim a rifle accurately while retreating from the enemy), and the control action can alter the way other capabilities are used (e.g., not being able to advance in a crouching posture limits the kind of ground cover one can hide behind).

PROJECTS USING THIS TECHNOLOGY

Many applications would benefit from the ability to walk through VE in a realistic manner. In the Team Tactical Engagement Simulator (TTES) developed by the Naval Air Warfare Center Training Systems Division (NAWC/TSD) and Southwest Research, military personnel practice urban warfare tactics [Horey Fowlkes, & Reir, 1995; Goodman, Porter, & Standridge, 1997]. The Naval Research Laboratory's Information Technology Division developed a VE of portions of the Ex-USS Shadwell, the Navy's full-scale fire research and test ship, to test the feasibility of using immersive VE as a tool for shipboard firefighting training and mission rehearsal [Tate, Sibert, William, King, & Hewitt, 1995]. Navy firefighters who practiced in the three dimensional model that included fire and smoke effects to simulate actual firefighting conditions performed better than those who only practiced using the ship's diagrams [Tate et al., 1997]. The University of North Carolina's Architectural Walkthrough System allows designers to explore a building design before its construction [Brooks *et al.*, 1992].

DIRECTIONS FOR THE FUTURE

We will continue to refine Gaiter. There are different ways of mapping the characteristics of in-place stepping to virtual stepping. We have initially adopted a linear mapping between the displacement of the knee while stepping in-place to the displacement of a virtual step. Further studies will be carried out to explore how well this matches natural stride lengths and stepping tempo. A variety of criteria will be used to measure the fit including the user's perceived rate of motion, the energy expended, or subjective effort made to move at different speeds.

We are developing an avatar driven by Gaiter. The avatar has two basic uses. It allows the user to see how his body fits into the VE, giving the user a better sense of immersion [Slater Usoh, & Steed, 1995]. An avatar also lets other people see the user's pose and location in VE. The challenge of developing an avatar driven by Gaiter is to match the control actions (in-place stepping) to the controlled effects (virtual stepping) in as natural a way as possible. The match will not be perfect and it remains to be seen how tolerant users will be to different kinds of mismatch.

CONCLUSIONS

There are many interactions between perceptual-motor systems and candidate locomotion controls involving looking, manipulating, turning the body, posturing, and thinking. These interactions limit the most promising approaches to those using the legs to make actions similar to natural locomotion. Our first attempt at building a leg-based control put too high a burden on the user to make special kinds of steps. We combined position trackers on the legs with the insole pressure sensors to create a walking simulator called Gaiter. Gaiter provides a consistent means of taking virtual steps in any direction. We will test our new virtual locomotion technique against two common sensor-based techniques: head-based steering and hand-based steering, both using finger pressure to control speed. The controls will be evaluated in terms of how similar peoples' actions in VE are using the control compared to peoples' actions in the real world.

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REFERENCES

Bowman, D., D. Koller, and L. Hodges (1997) Travel in Immersive Virtual Environments: an evaluation of view-point motion control techniques. *Proceedings of the Virtual Reality Annual International Symposium (VRAIS).*

Brooks, F. P., J. Airey, J. Alspaugh, A. Bell, R. Brown, C. Hill, U. Nimscheck, P. Rheingans, J. Rohlf, D. Smith, D. Turner, A. Varshney, Y. Wang, H. Weber, & X. Yuan (1992). *Six generations of building walkthrough: final technical report to the national science foundation.* (Tech. Rep. No. TR92-026). Chapel Hill, NC: Department of Computer Science, The University of North Carolina.

Darken, R. P., W. R. Cockayne, & D. Carmein (1997). The Omni-Directional Treadmill: A Locomotion Device for Virtual Worlds. Proceedings of UIST '97. pp. 213-221.

DiZio, P. and J. R. Lackner (1992) Spatial Orientation, Adaptation, and Motion Sickness in Real and Virtual Environments. *Presence, 1, 3,* 319.328.

Fairchild, K. M., B. H. Lee, J. Loo, H. Ng, & L. Serra (1993). The heaven and earth virtual reality: designing applications for novice users. *Proceedings of the IEEE VRAIS'93,* 47-53.

Goodman, S., S. Porter, R. Standridge (1997) Evaluation and Assessment of A Virtual Environment Advanced Technology Demonstrator. To appear in the Proceedings of ITSEC.

Horey, J., D. Fowlkes, & R. Reir (1995). Military operations on urbanized terrain (MOUT) training in synthetic environments using the team target engagement simulator (TTES). *Proceedings of the 17th Annual Interservice/Industry Training Systems and Education Conference,* 671-679.

Iwata, H., and T. Fujii (1996). Virtual perambulator: a novel interface device for locomotion in virtual environment. *Proceedings of the IEEE VRAIS"96,* 60-65.

Lampton, D. R., B. W. Knerr, S. L. Goldberg, J. P. Bliss, J. M. Moshell, and B. S. Blau (1994) The Virtual Environment Performance Assessment Battery (VEPAB): development and evaluation. *Presence, 3, 2,* 145-157.

Lorenze, M., D. Poole, R. Deaso, Y. Lu, A. Kekesi, J. Cha, D. Slayton, M. Williams, R. Moulton, V. Kaste, W. MacKrell, R. Paddison, J. Rieks, W. Roth, and F. Wodoslawsky (1995) OSIRIS. Proc. of the ACM SIGGRAPH'95 Visual Proceedings, 129.

Slater, M., M. Usoh, and A. Steed (September 1995) Taking Steps: The Influence of a Walking Technique on Presence in Virtual Reality. *ACM Transactions on Computer-Human Interaction, 2, 3,* 201-219 .

Tate, D. L., L. Sibert, F. W. Williams, LCDR T. King, and D. H. Hewitt (Oct. 1995) Virtual Environment Firefighting / Ship Familiarization Feasibility Tests Aboard the EX-USS Shadwell." NRL Ltr Rept 6180/0672.1.

Tate, D. L., Sibert, L., and LCDR T. King (1997). Virtual environments for shipboard firefighting training. *Proc. of the IEEE VRAIS'97,* 61-68.

Youngblut, C., R. E. Johnson, S. H. Nash, R. A.Wienclaw, & C. A. Will (1996) *Review of virtual environment interface technology.* (Tech. Rep. No. IDA Paper P-3186, Log: H 96-001239). Alexandria, VA: Institute for Defense Analyses.

Wells, M., B. Peterson, and J. Aten (1996) *The Virtual Motion Controller: A Sufficient-Motion Walking Simulator.* Technical Report: R-96-4. Human Interface Technology Laboratory.